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Impact of compressive fatigue on chloride diffusion coefficient in OPC concrete: An analysis using EIS method

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HIGHLIGHTS

- Electrochemical impedance spectroscopy is applied to evaluate concrete's fatigue damage.
- An electrical equivalent circuit is proposed to extract parameters from impedance spectra.
- An indicator (I_{DF}, $1/R_{CCP} + 1/R_{CP}$) is adopted to quantify the fatigue damage level.
- Relationships between chloride diffusion coefficients and I_{DF} are finally estimated.

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ABSTRACT

Fatigue damage is one of the most important factors impacting the chloride diffusion coefficient in concrete. In this paper, the electrical impedance spectra (EIS) method is used to analyze the damage level of the fatigue concrete. An electrical equivalent circuit is established to extract the electrochemical parameters from the impedance spectra. It is shown that the fitting results of the equivalent circuit match well with the experimental spectra. By analyzing the physical meanings of the parameters, the reciprocal of the overall resistance ($1/R_{CDP} + 1/R_{CCP}$) is finally adopted as an indicator of the fatigue damage level. Chloride diffusion coefficients of concrete undergoing fatigue damage were determined by a modified RCM method. It is found that the chloride diffusion coefficients decrease linearly with the overall resistances. The reduction in D_{RCM} is found to be rapid for the high w/c ratio (w/c 0.5) concrete and gradual for the low w/c ratio (w/c 0.36) concrete. It is also found that D_{RCM} increases nonlinearly with the indicator I_{DF}. The increasing rates get smaller when I_{DF} grows, and D_{RCM} has a maximum value when I_{DF} trends to infinity.

1. Introduction

Chloride ingress is one of the major causes of reinforcement corrosion which dominates the durability of reinforced concrete (RC) structures exposed to marine environments, salt lakes and de-icing salts [1–3]. Chloride diffusion coefficient is an important indicator for estimating the chloride-ingress resistance of the cover concrete of RC structures [4]. Thus, the value of chloride diffusion coefficient is critical for predicting the service life of RC structures exposed to the saline environments.

There are many factors being able to impact the chloride diffusion coefficient. Fatigue damage is one of the important factors that should not be ignored. Considering the actual service conditions, RC structures in most cases not only suffer from the chloride ingress but also withstand fatigue loads, e.g. wind loads, wave loads and loads of vehicles [5]. Fatigue will develop the micro-structural defects in concrete. The micro-structural defects will be accumulated little by little [6–8], and thereby exponentially decreasing the chloride-ingress resistance of the cover concrete [9,10]. Knowing this, it is considered to be urgent to study the impact of fatigue damage on chloride diffusion coefficients.

Up to present, many researchers have investigated the impact of the static loads on chloride diffusion coefficients. However, the studies concerning the impact of fatigue loads are still insufficient. Among the insufficient studies, most researchers [11–14] merely used the fatigue cycles as the indicator of damage, by which the impact of fatigue damage on chloride diffusion coefficient could only be qualitatively comprehended. In fact, the fatigue cycles cannot exactly represent the level of fatigue damage. Thus, it is necessary to find a rational indicator to represent the level of fatigue

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damage so as to establish the quantitative relationship between fatigue damage level and chloride diffusion coefficient.

In this paper, the electrical impedance spectra (EIS) method is used to analyze the damage level of the fatigue OPC concrete. For fitting the experimental impedance spectra, an electrical equivalent circuit is established according to the realistic test situations. The electrochemical parameters are extracted from the impedance spectra by using the established equivalent circuit. After analyzing the physical meanings of the electrochemical parameters, a function of these parameters is defined as the indicator of fatigue damage. Then the relationships between chloride diffusion coefficients and the indicator values are finally estimated.

2. Materials and methods

2.1. Materials and concrete mixes

Ordinary Portland cement manufactured in China (Chinese standard GB175-2007) was used and the chemical composition of the cement is shown in Table 1. River sands with a fineness modulus of 2.8 were used as the fine aggregate. Gravels with a maximum size of 20 mm are utilized as the coarse aggregate. Moreover, the detailed concrete mixes are given in Table 2.

2.2. Preparations of specimens

Prism specimens were prepared into two different sizes (size-A: 100 mm × 100 mm × 100 mm, size-B: 100 mm × 100 mm × 400 mm). For each concrete mix, three size-A prism specimens were cast to determine the compressive strength, thereby designing the maximum load of the fatigue test. Several dozens of size-B specimens were cast for the fatigue and the following EIS, RCM tests.

After casting, all the specimens were covered with a polythene sheet and stored in the laboratory air (typically at 15–20 °C, 50–55% relative humidity) for 24 h and subsequently demoulded. After that, the specimens were cured in saturated lime-water at 20 ± 1 °C for 28 days.

Table 1
Composition of cement.

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	LOI
54.28	23.57	9.34	3.1	1.35	1.03	0.11	3.99	3.16

2.3. Fatigue test

Fatigue specimens were tested in an electro-hydraulic-servo testing machine under load control using sinusoidal loading at a frequency of 5 Hz, which is shown in Fig. 1. The applied stress levels were 50%, 60%, 70% and 75%; the fatigue cycles generally included 5000times, 10,000 times, 15,000times, 20,000 times, 30,000 times and 40,000 times; the characteristic value of cyclic loading was set to 0.1, i.e. $|\sigma_{min}|/|\sigma_{max}| = 0.1$. The detailed load controls are given in Table 3.

2.4. EIS test

After fatigue test, two cube specimens (100 mm × 100 mm × 100 mm) were cut from the middle part, where the stress distribution is considered to be more uniform, of each size-B specimen. One of the two cube specimens was temporarily stored for RCM test, which will be introduced in the next section, while the other was used here for EIS test. Prior to EIS test, two opposite testing surfaces, which were perpendicular to the casting surface and the loading direction, were grinded first and then bonded with 100 mm × 100 mm × 0.3 mm copper sheets using a graphite conductive adhesive. On each copper sheet, a conductive wire was welded to connect to the electrochemical workstation. When the conductive adhesive was dried, the specimen was put into a water tank for 72 h to reach a water-saturated condition. Then the specimens were taken out and sealed by epoxy resin and polythene sheets. A ready-for-use specimen is shown in Fig. 2.

EIS test was conducted via a Parstat 2273 Advanced Electrochemical Workstation. The scanning was carried out on the two-electrode cell by applying a sinusoidal potential perturbation of 5 mV at the open circuit potentials with a frequency range from 100 kHz to 10 mHz (40 points total). After that, the EIS spectra were analyzed with an equivalent-circuit to obtain the electrochemical parameters by ZsimpWin software.

Table 2
Concrete mix.

No.	w/c	Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water reducer (%)	28d compressive Strength (MPa)	Slump (mm)
C1	0.36	403	145	746	1119	0.5	56.3	92
C2	0.50	322	161	752	1128	–	36.1	85

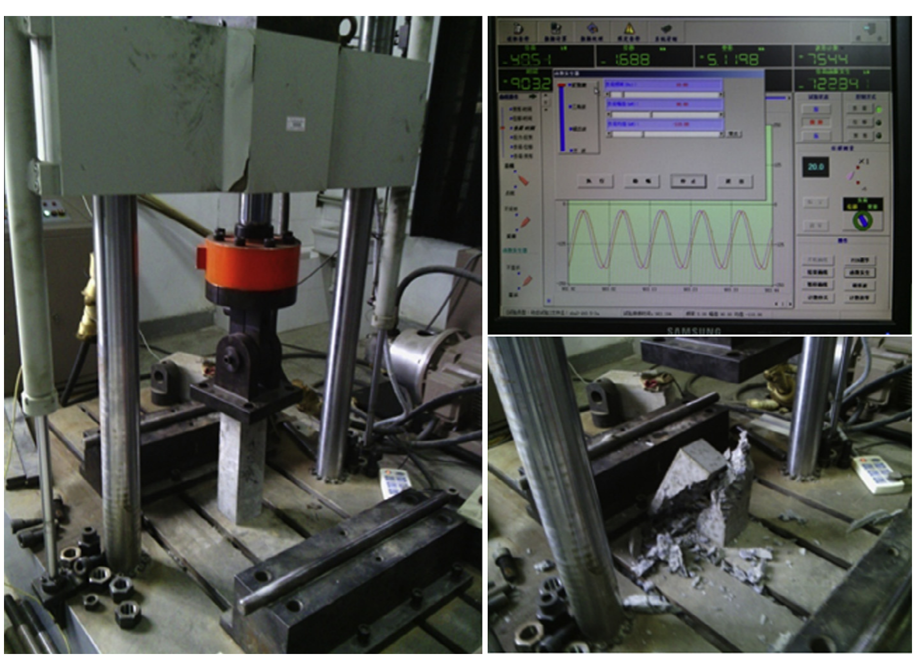

Fig. 1. Equipment of compressive fatigue test.